Lattice for strongly coupled beyond-the-standard-model theories

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for the USQCD Collaboration
LQCD-EXT II Annual Review
June 28, 2016

(recent reviews: T. DeGrand, 1510.05018; G.D. Kribs and E.T. Neil, 1604.04627)

Science drivers: a lattice model builder's perspective

- From the P5 report, **five drivers** for particle physics:
  - **Use the Higgs boson as a new tool for discovery**
  - **Pursue the physics associated with neutrino mass**
  - **Identify the new physics of dark matter**
  - **Understand cosmic acceleration: dark energy and inflation**
  - **Explore the unknown: new particles, interactions, and physical principles.**

BSM model building

- Models of new physics are used to interpret/guide experiment, connect between different drivers
- Many such models contain strongly-coupled interactions. Explore non-perturbatively using lattice!

Lattice and EFTs for strongly-coupled new physics

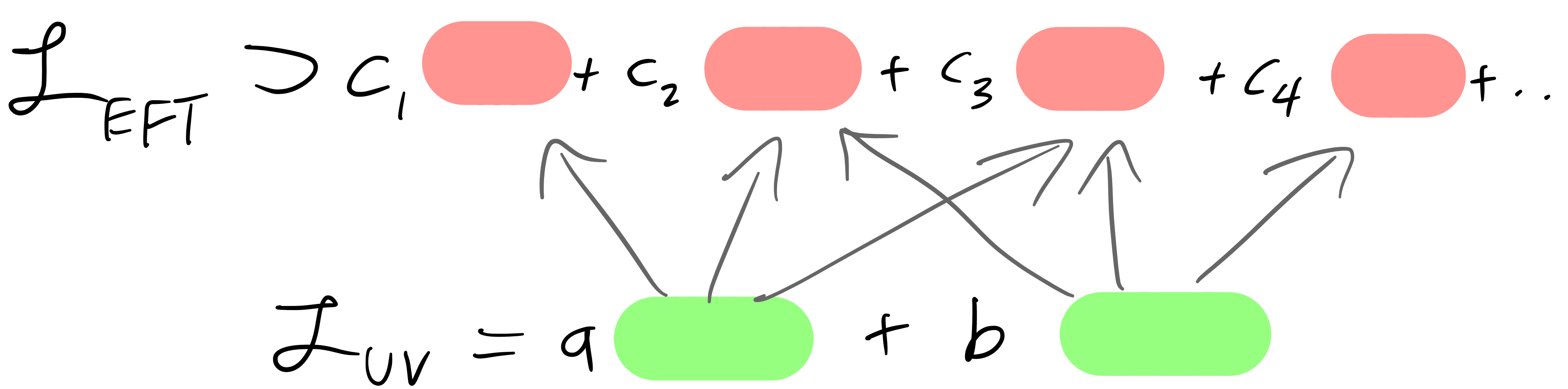
- Can usually study models <u>analytically</u> at low energies by using effective field theory (**EFT**): collider studies, dark matter direct detection, etc.

- Quantitative power of EFT approach is limited; predictive power relies on matching many (infinite!) low-energy constants (LECs) to experiment.

- Using lattice to study UV-complete models can go further in two important ways:

  1. <u>Determine LECs</u> of the EFT from a handful of fundamental parameters (e.g., from quark masses and strong coupling in lattice QCD)

  2. <u>Reveal dynamical surprises</u> that tell us we were missing something in our EFT description (e.g. a new state), or even had the wrong EFT (vacuum structure)

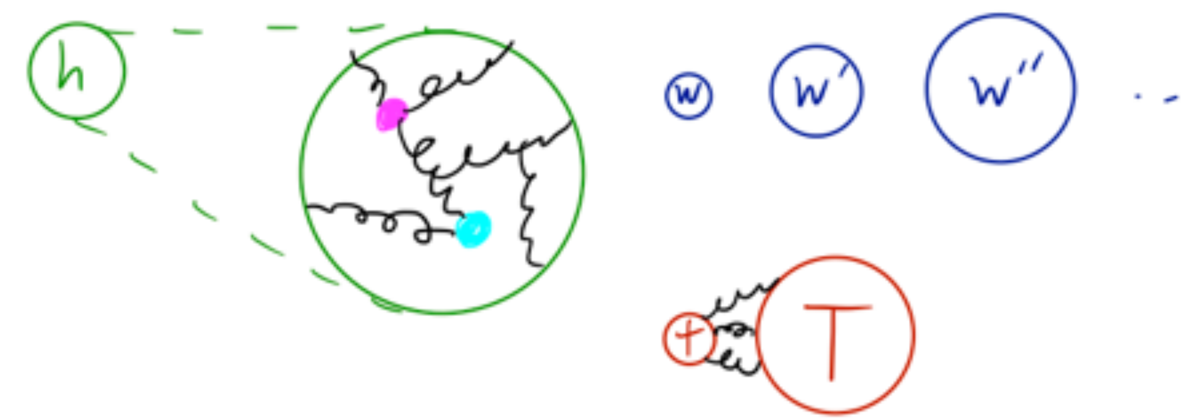


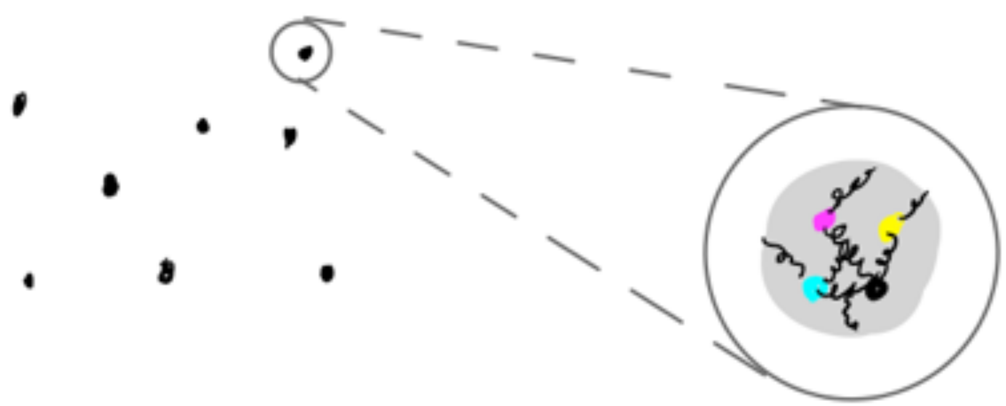
Overview: USQCD BSM program

Current efforts are divided roughly into three topic areas:

(1) Composite Higgs

Solution to SM Higgs hierarchy problem: Higgs is a composite bound state of new strongly-coupled particles.





(2) Composite dark matter

Solution to lack of SM dark-matter candidate: can appear naturally from composite Higgs or grand unified theories.

(3) Supersymmetry ("SUSY")

Solution to SM Higgs hierarchy problem: superpartners near electroweak scale. Strong coupling appears in dynamical SUSY breaking.

(Other smaller efforts: quantum gravity, large-N gauge theories, conformal field theories)

Overview: USQCD BSM program

Current efforts are divided roughly into three topic areas:

(1) Composite Higgs

Solution to SM Higgs hierarchy problem:

(1,2,3,…) Strongly-coupled quantum field theory

Exploring the rich dynamics of QFT at strong coupling cuts across all models; lattice is the only available non-perturbative definition

We learn about strong dynamics from lattice, even if BSM model *X* is ruled out. *(Like exploring QCD at non-physical quark mass.)*

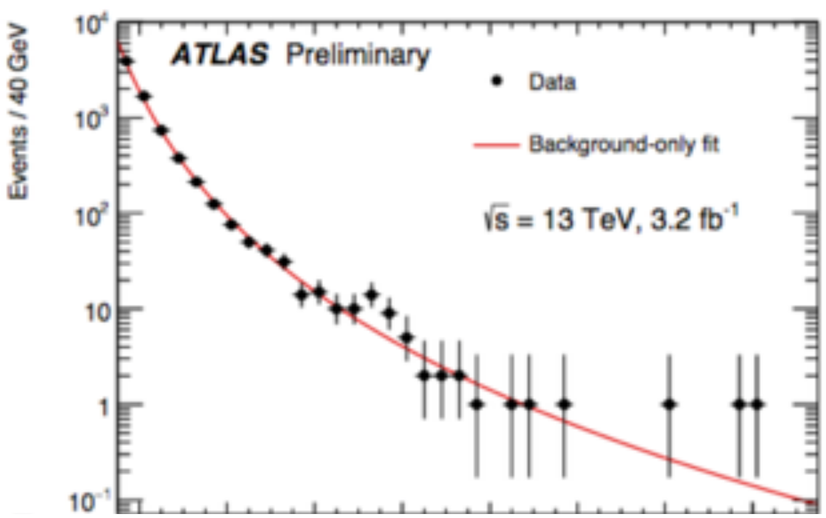
Need to develop tools for studying strongly-coupled QFT now, to be ready for possible discovery at the LHC or elsewhere!

(Other smaller efforts: quantum gravity, large-N gauge theories, conformal field theories)

Interaction between lattice BSM/pheno communities

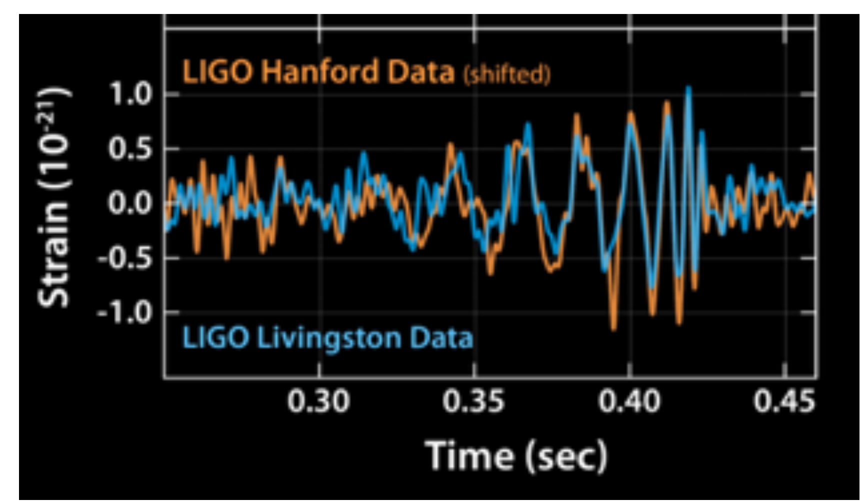
- Sharply increasing interest from BSM model builders in strongly-coupled, UV-complete models in the last few years!

- Pheno+experiment can generate new questions for us, such as:



Do composite models contain isolated diphoton-resonance candidates?

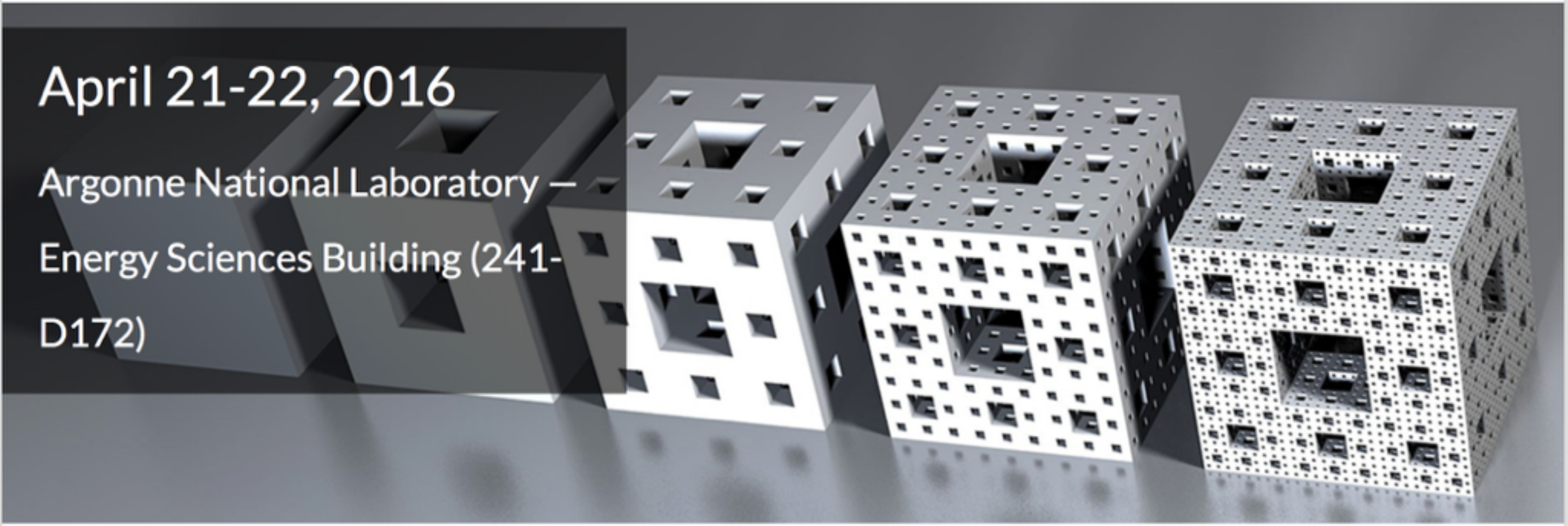
Can composite dark matter source observable primordial gravitational waves?



- Flexibility needed, since “true” theory not yet known. Motivates broad exploration of many possibilities now, focusing as experimental situation becomes clearer.

Lattice for Beyond the Standard Model Physics 2016

Home Agenda Registration Participants Local Information



- Seventh workshop in a series, connecting lattice BSM community to phenomenologists, experimentalists. 37 participants.
- Balance of talks: **11** lattice, **7** pheno/theory, **1** experimental (LHC)

Scientific Organizing Committee

Thomas Appelquist (Yale)
Yang Bai (Wisconsin)
Simon Catterall (Syracuse)
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Ethan Neil (Colorado)
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Pavlos Vranas (LLNL)

Local Organizing Committee

Xiao-Yong Jin (ANL)
Ethan Neil (Colorado)
James Osborn (ANL)
Pavlos Vranas (LLNL)

Lattice BSM in the pheno literature:

PRL 115, 181101 (2015) PHYSICAL REVIEW LETTERS week ending 30 OCTOBER 2015

Gravitational Waves from a Dark Phase Transition

Pedro Schwaller

CERN, Theory Division, CH-1211 Geneva 23, Switzerland

(Received 1 June 2015; revised manuscript received 2 September 2015; published 26 October 2015)

A shortcoming of the present work is a lack of precise quantitative predictions. The bubble velocity v as well as the time scale of the phase transition β^{-1} and the energy fraction Ω_{S*} are currently unknown, and are set to optimistic (but not unrealistic) values. Two approaches seem possible to improve upon this situation: On one side, lattice simulations could be used to measure quantities like the latent heat and the surface tension, which are related to the above parameters and can be used to obtain a more quantitative prediction for the GW spectra. Alternatively, one could attempt to construct a holographic dual for some of these theories, and analyse the PT in that setup.

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UV completions of partial compositeness: the case for a SU(4) gauge group

Gabriele Ferretti

The main omission in this work is that we do not attempt to show that the anomalous dimensions for the composite operators are sufficient to realize a realistic mass spectrum, although arguments in favor of this possibility have been recently proposed in [13] for a similar model. Convincing evidence on this issue can only come via lattice simulations or a detailed analysis of the OPE that is beyond

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Published: March 31, 2016

Fundamental composite 2HDM: SU(N) with 4 flavours

Teng Ma[a,b] and Giacomo Cacciapaglia[c,d]

guiding the building of the low energy chiral Lagrangian, and it can be simulated on the Lattice in order to have non-perturbative predictions of the spectrum. The need for numerical prediction is in fact essential for studying the viability of such models *vis a vis* the results at the LHC.

Prepared for submission to JHEP

A "dangerous irrelevant" UV-completion of the composite Higgs

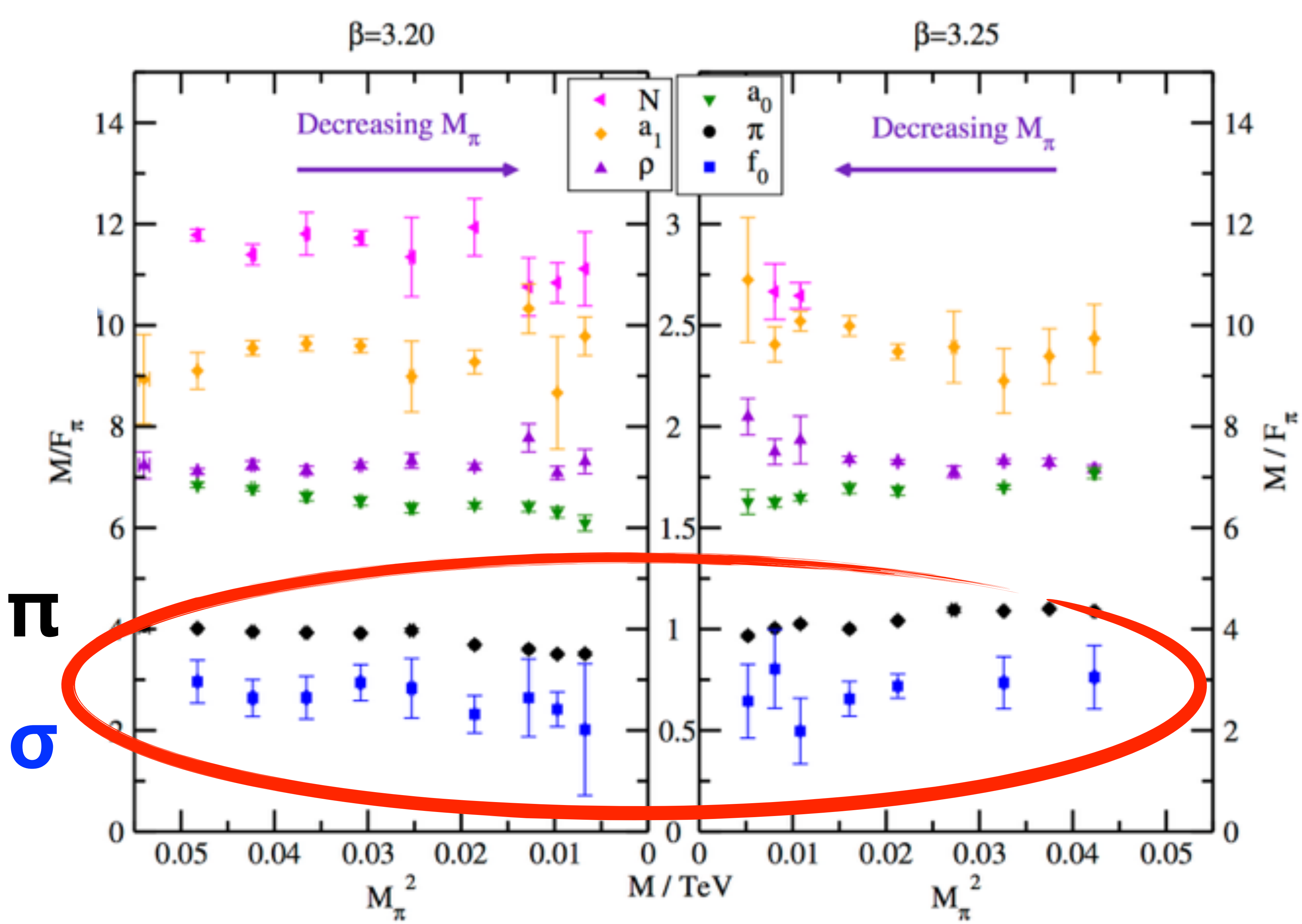
Luca Vecchi

that makes λ more relevant. It is a little premature to determine which of these approaches offers the most compelling realization of PC. For this reason lattice simulations should ideally be performed on as many theories (and fermionic operators $\psi_1\psi_2\psi_3$, $G^a_{\mu\nu}\sigma^{\mu\nu}\psi^a$, etc.) as possible.

(plot from LatHC Collaboration, SU(3) "sextet" model)

USQCD Science Highlights: Light 0++?

A composite Higgs (spin-0, PC=++) must be light compared to other predicted resonances not yet seen. One option is construction as Goldstone mode from chiral symmetry breaking, like the QCD pions (e.g. little Higgs.) Is there another possibility?



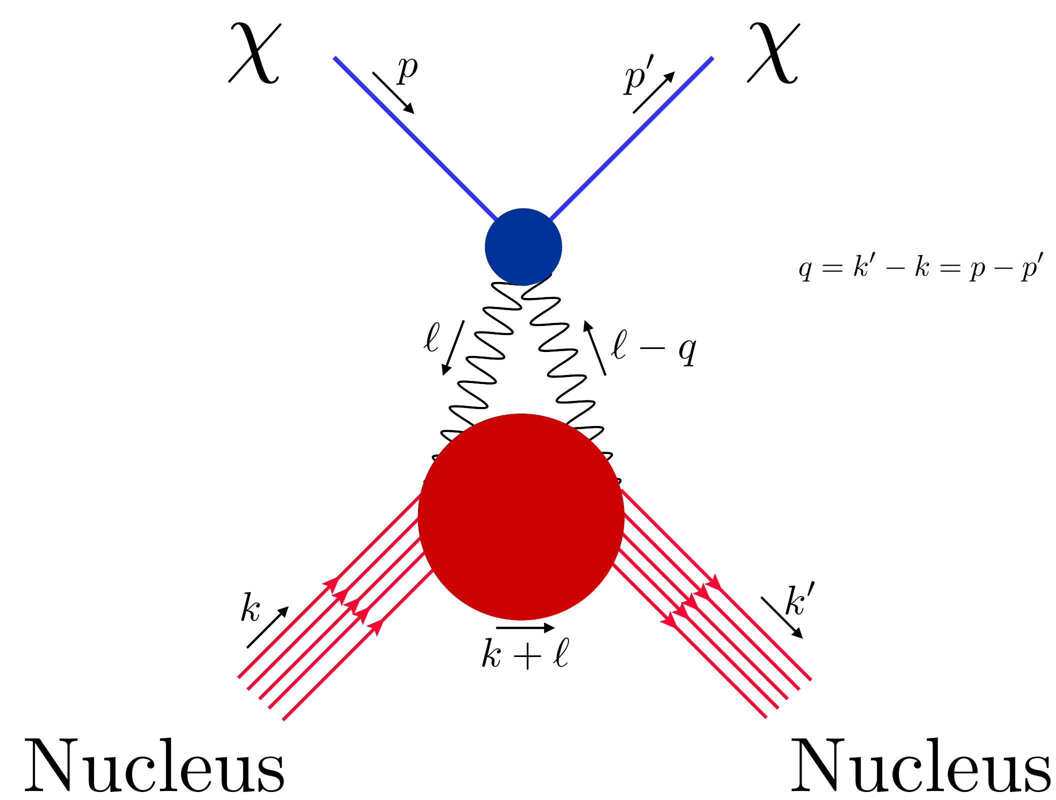
Sigma (0^{++}) state is near-degenerate with the pions in these theories!

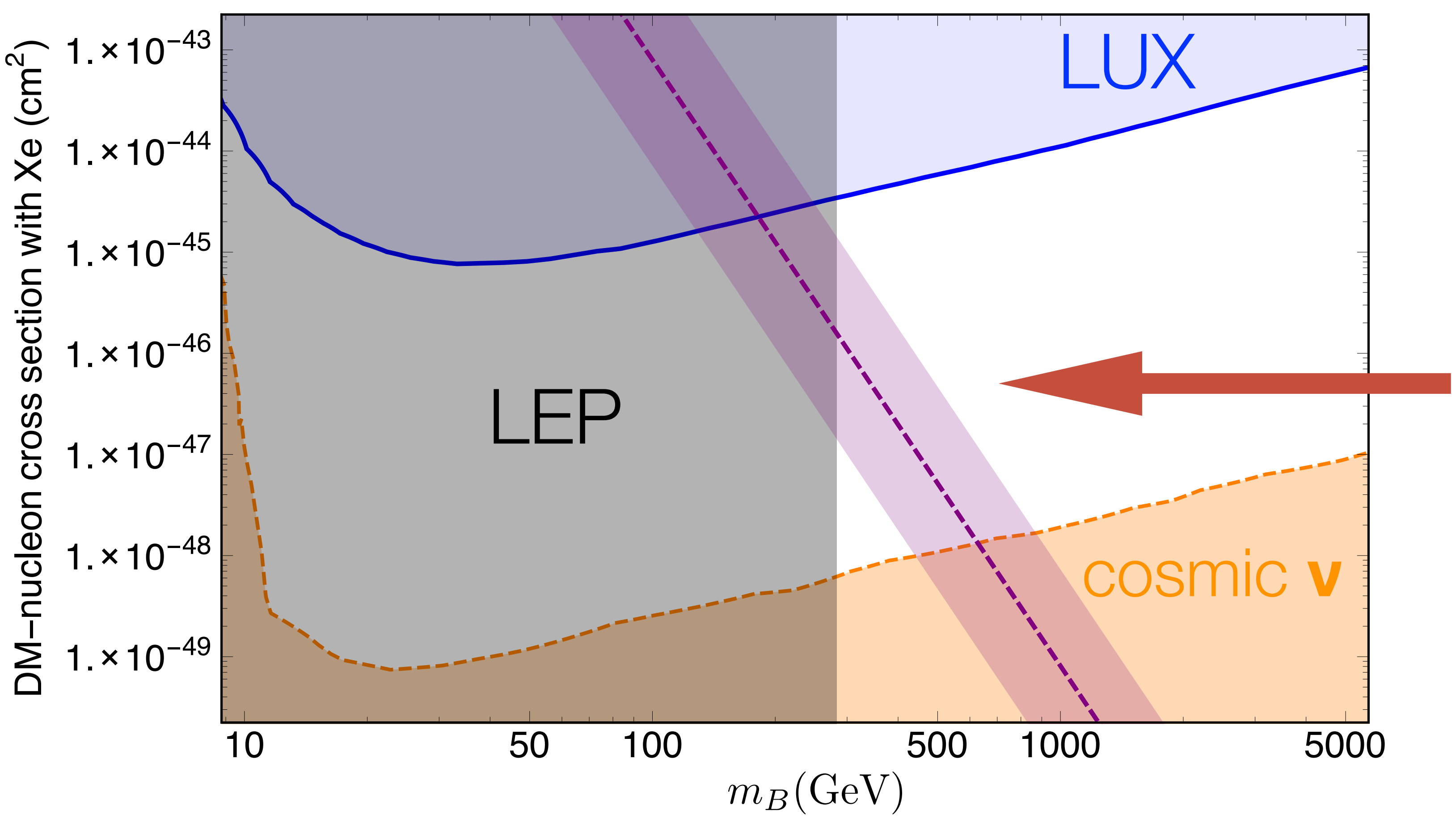
Is this system well-described by a low-energy EFT including the sigma as well? What is the effective theory? Only lattice can answer!

(plots from LSD Collaboration, Phys. Rev. Lett. 115 (2015), arXiv:1503.04205)

USQCD Science Highlights: DM Polarizability

- How does composite DM interact with us? Can have large SM charges, active in early-universe plasma. Today, small interactions due to form-factor suppression.
- With underlying Z_2 symmetry, leading interaction can be two-photon polarizability - unusually, scattering occurs at loop level.



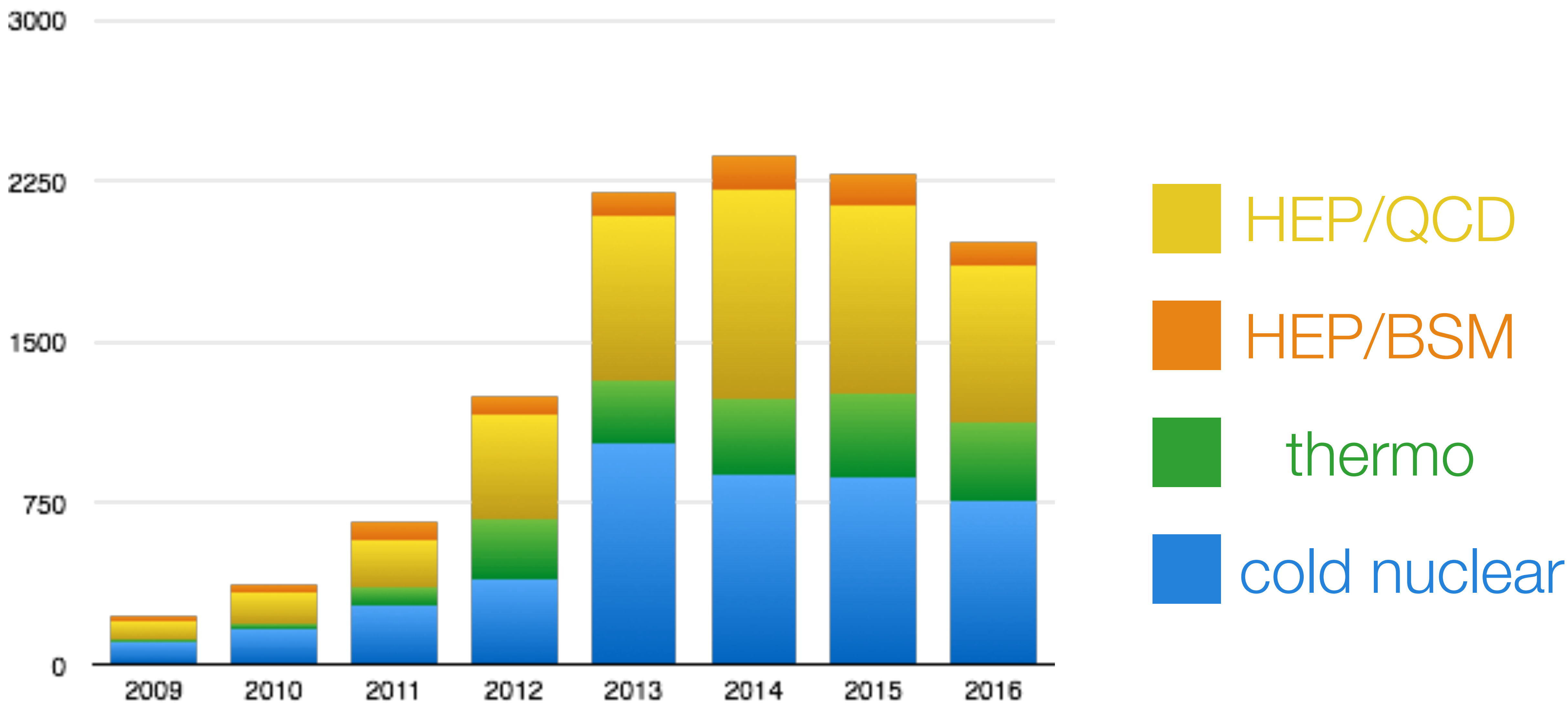


Cross section O(100) larger than naive dimensional analysis estimate!

"Stealth dark matter" can be detected up to ~TeV; wouldn't have known without lattice!

*T. DeGrand, Rev. Mod. Phys 88, 1510.05018
G.D. Kribs and E.T. Neil, Int. J. Mod. Phys. A (in press), 1604.04627

Computing resources



- Since Jan. 2015, **28** papers published or posted to arXiv from USQCD lattice BSM program, **10** journal publications (not proceedings), **1** PRL (editors' suggestion) - see backup slides. Not counted in the above: **2** invited review articles on lattice BSM*.

- Substantial scientific output for small fraction (5-10%) of resources! Reasonable investment for future-looking, curiosity-driven research that stress-tests lattice machinery.

Science drivers: questions for lattice model builders

Over the next five years, our goal is to obtain lattice answers to the following non-perturbative questions in each topic area (further details in backup slides):

1) Composite Higgs

- What dynamics yields a Standard Model-like Higgs light relative to other new resonances ("little hierarchy")?
- How large are the non-perturbative matrix elements that determine Standard Model fermion masses?
- What are the other lowest-energy composite states? How can the LHC search for them?

2) Composite dark matter

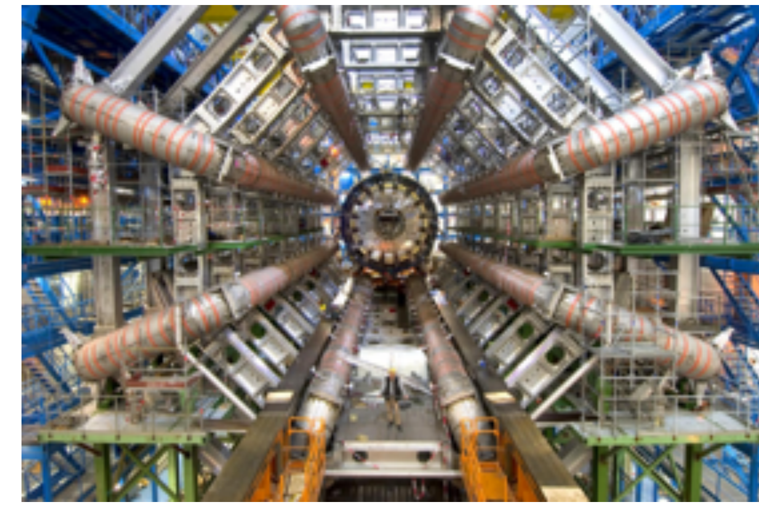
- What are the "form factors" of composite dark particles that control their interactions with SM states?
- Under what circumstances can stable "dark nuclei" form?
- What are the properties of the dark thermal phase transition? Can it generate observable gravity waves?

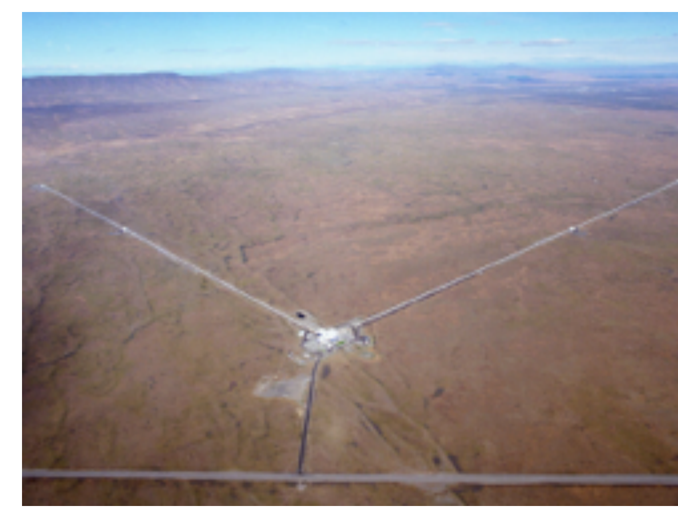
3) Supersymmetry

- Can we provide non-perturbative tests of phenomena in supersymmetric theories, like the S-duality conjecture?
- What can we learn about the emergence of dynamical SUSY breaking from strongly-coupled supersymmetric theories?

Summary

- Experiments are running with unprecedented energy and precision; now is the time to develop tools for BSM theory!
- Lattice can handle strong coupling, which is ubiquitous in BSM models; studies can give general insight into strongly-coupled QFT.
- Small proportion of USQCD resources go to lattice BSM, but this is big relative to other local sources - USQCD support is crucial!





Backup slides

Detailed scientific targets: composite Higgs

1. Identify the most likely candidates in the spectrum for LHC discovery in the theories we are currently studying. Compute matrix elements for their decay widths, and study the most promising search channels (e.g. diphoton for spin-0 resonances.)

2. Study the emergent low-energy effective theory of pions and the light 0++ "sigma". Calculate the interactions between these states, and see if they match predictions from known EFTs such as the linear sigma model or chiral perturbation theory.

3. Calculate anomalous dimensions and "baryon"-to-vacuum matrix elements, for theories of partial compositeness. Begin with theories that have proposed UV completions: SU(3) with 4 light fermions, and SU(4) with fermions in fundamental and antisymmetric reps.

Detailed scientific targets: composite dark matter

1. Determine the binding energy of light nuclei in SU(4) gauge theory, extending known results for QCD and for SU(2). Use the results to study whether large-N expansion is effective here.

2. Calculate finite-temperature transition properties (transition order, latent heat, etc.) in a candidate dark matter theory, e.g. SU(4) “stealth DM”. Match on to gravitational wave predictions, predict possible signals for future gravitational wave observatories.

3. Determine meson electromagnetic form factors in SU(4) gauge theory. Test the usefulness of vector-meson dominance in theories other than QCD. Make predictions for collider production rates and for indirect detection via dark matter annihilation.

Detailed scientific targets: lattice SUSY

1. Compute the conformal dimensions of various primary operators in superconformal phase of N=4 Yang-Mills, e.g. the Konishi - lightest flavor singlet scalar operator. Compare non-perturbative results to conformal bootstrap bounds, and to large-N prediction (Bethe ansatz).

2. Investigate the lattice beta function for N=4 Yang-Mills using Monte Carlo Renormalization Group methods. Determine what fine tuning is needed to restore full supersymmetry in continuum limit.

3. Study the scaling of the static potential at large N; test for evidence of Maldacena scaling.

4. Compute the W boson and monopole masses on the Coulomb branch of the theory. In combination with (1), provide a direct test of the weak-strong (S) duality conjecture. Also, test electric/magnetic line operator duality.

5. Make contact with string/supergravity theory through holographic connections. Pursue any lattice results at finite N where corrections to leading SUGRA results from the string-theory side can be studied.

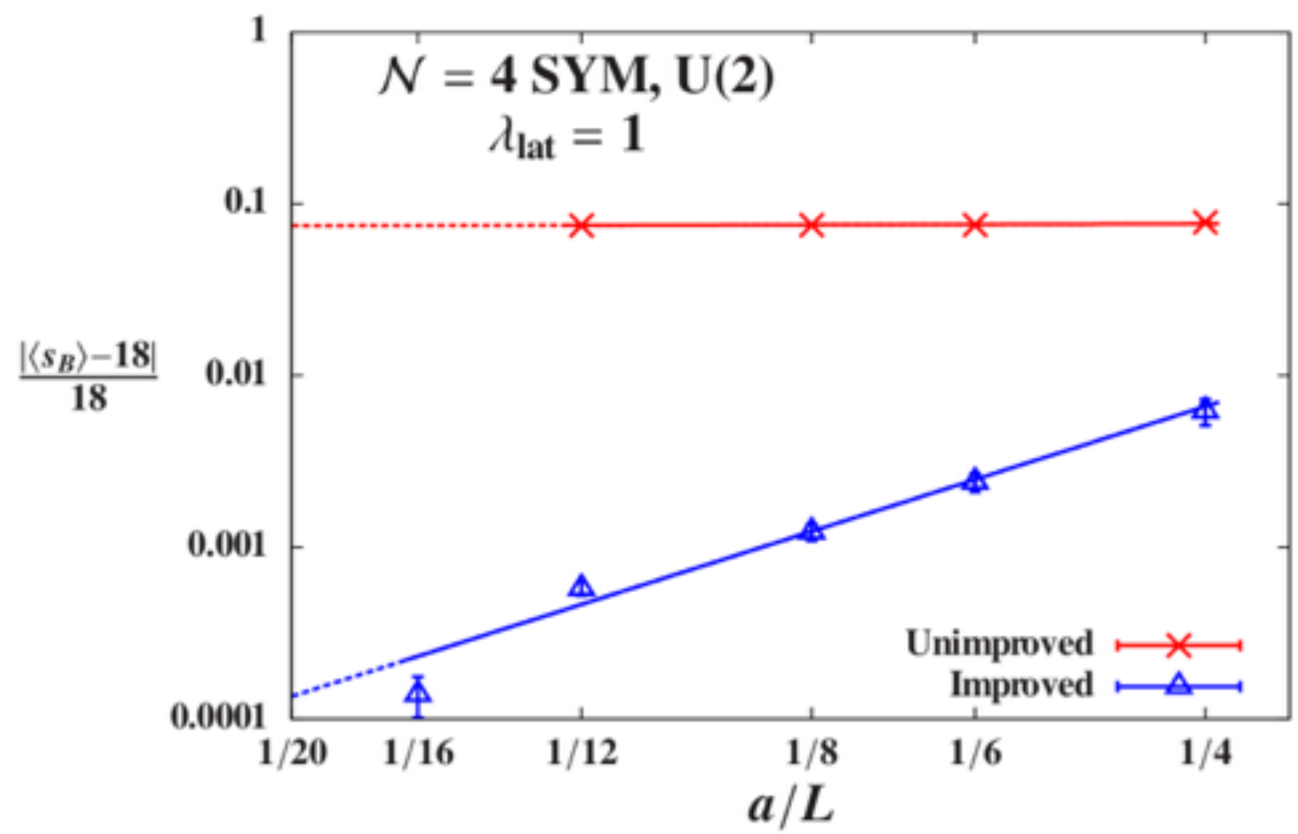
(public code: https://github.com/daschaich/susy)

USQCD Highlights: N=4 lattice SUSY

- Supersymmetry is notoriously difficult to study using lattice, which explicitly breaks space-time symmetries

- "Twisted" formulation of N=4 SYM in four dimensions exactly preserves one supersymmetry at finite lattice spacing; other 15 symmetries restored in continuum limit

*S. Catterall and D. Schaich, 1505.03135



- Recent breakthrough* in formulation of the lattice action allows lifting of "flat direction" in field space while preserving SUSY; shown to massively improve SUSY-breaking artifacts and rate of approach to continuum limit

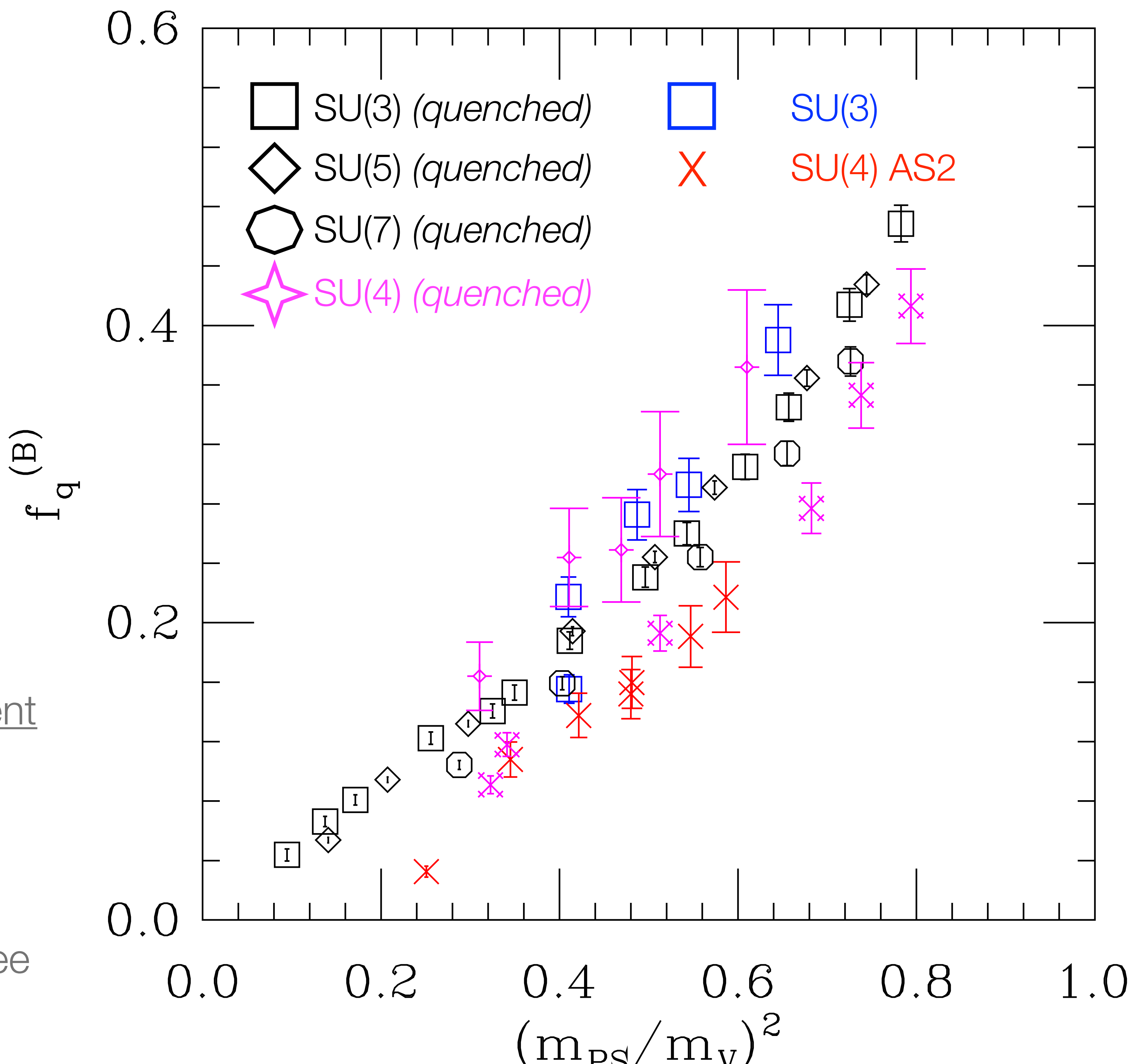
- Large-scale simulations with improvement are the next step!

USQCD Highlights: composite DM/Higgs exchange

- Where does DM mass come from? Higgs mechanism —> Higgs coupling, constraint from direct detection.
- Straightforward for fundamental DM, but composite DM-Higgs coupling requires a non-perturbative matrix element ("sigma term"):

$$f_f^B = \frac{m_f}{M_B} \frac{\partial M_B}{\partial m_f}$$

- Lattice results now hint that this matrix element may be fairly universal for different theories in similar mass regimes (right)
- Indication that Higgs as lone source of fundamental fermion mass in composite dark sector is ruled out very generally (see arXiv:1604.04627)



[T. DeGrand, Y. Liu, EN, B. Svetitsky, Y. Shamir, Phys. Rev. D 91, 114502 (2015)] [find a (...) and date >= 2015]

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